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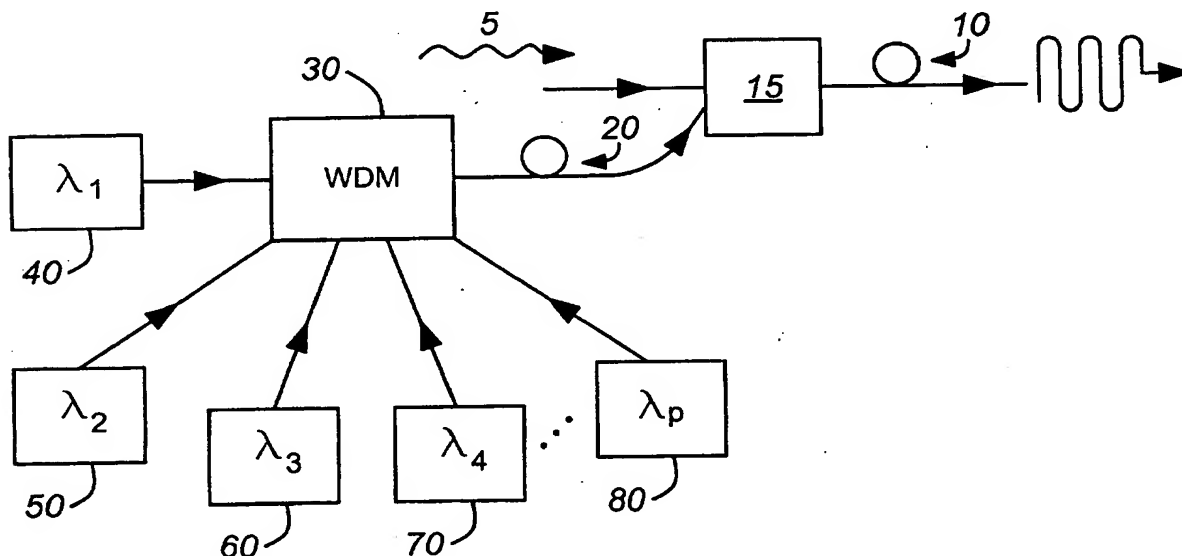
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(54) Titre : SOURCE LUMINEUSE COHERENTE A LONGUEURS D'ONDES MULTIPLES POUR AMPLIFICATION
RAMAN

(54) Title: COHERENT MULTI-WAVELENGTH LIGHT SOURCE FOR RAMAN AMPLIFICATION



(57) Abrégé/Abstract:

The instant invention relates to a high power, multi-wavelength source for use with a distributed Raman amplifier. The combination of high power and multi-wavelength is accomplished via Raman amplification of a plurality of single wavelength lasers. A high power light source is used to pump the Raman amplifier. The amplifier is designed to shift the frequency of the pump and provide amplification in the spectral range of the plurality of single wavelength lasers. The single wavelength sources are injected into the amplifier with a wavelength division multiplexer (WDM). Advantageously, this device improves low noise operation.

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Abstract of the Disclosure

The instant invention relates to a high power, multi-wavelength source for use with a distributed Raman amplifier. The combination of high power and multi-wavelength is accomplished via
5 Raman amplification of a plurality of single wavelength lasers. A high power light source is used to pump the Raman amplifier. The amplifier is designed to shift the frequency of the pump and provide amplification in the spectral range of the plurality of single wavelength lasers. The single wavelength sources are injected into the amplifier with a wavelength division multiplexer (WDM). Advantageously, this device improves low noise operation.

Coherent Multi-wavelength Light Source for Raman Amplification

Field of the Invention

- 5 This invention relates generally to optical amplifiers, and more particularly to a high power, multi-wavelength light source for use with optical fibre Raman amplifiers.

Background of the Invention

- 10 Optical amplifiers are well known and play a fundamental role in optical fibre telecommunication systems. In particular, optical amplifiers are attractive alternatives to other amplifiers because they amplify the optical signals without converting the optical signal into a corresponding electrical signal.
- 15 One common example of an optical amplifier is the rare-earth doped optical fibre amplifier. In a rare-earth doped optical fibre amplifier, the transmission fibre is doped with a rare earth, such as erbium (Er) or ytterbium (Yb), and a light source, which is typically a laser diode, "pumps" energy into the doped optical fibre. The light provided by the "pump" laser diode is absorbed by the erbium atoms in the transmission fibre, pumping those atoms to a high-energy level. When a
- 20 weakened signal passes through the transmission fibre, the excited erbium atoms transfer their energy to the signal in a process known as stimulated emission. Advantageously, erbium doped fibre amplifiers (EDFAs) have high, polarization insensitive gain, low cross talk between signals of different wavelengths, and good saturation output power. Disadvantageously EDFAs generally have a narrow spectral width and yield undesirably high noise levels.
- 25 Another common example of an optical amplifier is the Raman amplifier. In the Raman amplifier, the optical transmission medium is excited via stimulated Raman scattering (SRS). Stimulated Raman scattering is an inelastic scattering process, wherein the energy from a high power light source of wavelength λ_1 is transferred to molecular vibrations of the transmission
- 30 medium (i.e., optical phonons) and light having radiation of wavelength λ_2 . The optical signals

are amplified via stimulated emission. Since, signal amplification occurs along the signal transmission path, Raman amplifiers are generally classed as distributed amplifiers.

In optical amplifiers exploiting stimulated Raman scattering, a high power "pump" light (λ_p) and
5 a lower power optical signal (λ_s) are introduced into the same optical transmission fibre. The energy from the high power pump light (λ_p) is transferred to the lower power optical signal (λ_s), thus amplifying the signal. The pump light and the optical signal are launched through the optical transmission fibre in either a co-propagating or a counter-propagating configuration. Typically, λ_p is less than λ_s and the difference between λ_p and λ_s is designed to be approximately
10 equal to the Stokes shift of the transmission medium. That is, pump energy of a given wavelength amplifies a signal at a longer wavelength (lower energy/frequency). Since the fibre medium is typically silica glass, which is generally amorphous in nature, the Stokes shift and the resulting spectral range is relatively broad. Obviously, the presence of other components, such as dopants and/or Bragg gratings, affects the spectral range.

15 Raman amplifiers have a number of advantages over EDFAs. The first advantage is related to the above-mentioned broad spectral range. In fact, Raman amplifiers are capable of operating over the entire transparency range for optical fibres, in particular, they operate well in both of the two main low-loss telecommunication windows (i.e., 1310 and 1550 nm). This is in contrast to
20 EDFAs, which are typically limited to the 1550 nm window.

A second advantage of Raman amplifiers is that they can be pumped at various wavelengths since there is no pump absorption band associated with the fibre and/or dopant(s). In fact, Raman amplifiers have the advantage that the gain shape and spectral width are controlled by
25 appropriate choice of pump wavelength and pump power at a given wavelength.

Other advantages of Raman amplifiers compared to EDFAs relate to the fact that Raman amplifiers provide increased signal-to-noise ratios, thereby increasing the distance between optical amplifiers, enabling transmission rate upgrades of installed systems, and allowing lower
30 signal powers to be used. In addition, Raman amplifiers become only moderately lossy in the event of power failure, in contrast to Er doped amplifiers.

Despite the above-mentioned advantages, the practicality of Raman amplifiers has been limited by the conflicting need for a sufficiently powerful pump source and a reasonably controllable gain shape. In fact, there remains a need for a Raman pump source with increased pump power that provides increased bandwidth and controllable gain shape.

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U.S. Patent No. 6,052,219 and U.S. Appl. Ser. No. 09/030,994, incorporated herein by reference, disclose a Raman amplifier having two pump sources providing pump energy at two or more different wavelengths, which are used to generate two overlapping gain curves that form a composite gain spectrum having a bandwidth that is greater than either of the individual gain
10 curves. Although, these amplifying devices are capable of providing an optical amplifier with an increased bandwidth and somewhat controllable gain shape/profile, they are limited by the cost and availability of high power pump sources. In particular, these devices are limited by the availability of high power semiconductor diode lasers, and the passive losses of components used to combine these diode lasers. In fact, the current state of the art does not yet allow the
15 fabrication of reliable single mode laser diodes with output power greatly exceeding 250 mW that have operating lifetimes suitable for optical fibre communication systems.

U.S. Pat. No. 5,323,404, incorporated herein by reference, discloses both cascaded Raman lasers and cascaded Raman amplifiers. These devices include one or more pairs of spaced apart
20 reflectors, such as Bragg reflectors, that provide one or more optical cavities in the hosting optical fibre. These cavities provide exceptionally high power pump energy that is suitable for distributed Raman amplification. By varying the pump wavelength or by using cascaded orders of Raman gain, the gain can be provided over the entire telecommunications window between 1300 nm and 1600 nm. Nevertheless, these resonators are typically designed so that only one
25 wavelength is lasing. The use of multiple cascaded Raman lasers for controlling the gain shape is cost prohibitive, and hence, the gain shape is not easily tuned using a plurality of Raman lasers/resonators.

It is an object of the instant invention to provide a simple optical amplifying system with
30 increased pump power, increased bandwidth, and reasonably controllable gain shape.

It is another object of the instant invention to provide a multi-wavelength, high power light source for use with a fibre amplifier, and in particular, for use with a distributed fibre Raman amplifier.

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Summary of the Invention

The instant invention relates to a high power, multi-wavelength pump source for use with a distributed Raman amplifier. The combination of high power and multi-wavelength pumping is accomplished via Raman amplification of a plurality of single wavelength lasers. A high power light source is used to pump the amplifier. The amplifier is designed to extract energy from this pump and provide amplification in the spectral range of the plurality of single wavelength lasers. The single wavelength sources are optionally injected into the amplifier with a wavelength division multiplexer (WDM).

15

Although the multi-wavelength high power source of the instant invention is particularly well suited to systems that employ distributed Raman amplifiers, the invention should not be limited thereto. For example, the high power, multi-wavelength pump source of the instant invention is equally suitable for other amplifiers, including rare-earth doped fibre amplifiers such as EDFAs. Similarly, the instant invention is particularly well suited for amplifying multiplexed signals, however, applications to single wavelength systems are not excluded.

20

In accordance with the invention there is provided an optical amplifying system comprising:

- a first Raman amplifier for amplifying an information-bearing optical signal; and
- a second Raman amplifier optically coupled to the first Raman amplifier for amplifying a non-information-bearing optical signal for pumping the first Raman amplifier.

25

In accordance with the invention there is provided a pump source for optical fibre amplification comprising:

- a first pump source for providing pump radiation at a first wavelength λ_1 ,
- a second pump source for providing pump radiation at a second wavelength λ_2 ; and

30

a cascaded Raman amplifier optically coupled to the first and second pump sources for allowing the pump radiation at wavelength λ_1 to be shifted to about wavelength λ_2 via stimulated Raman scattering and for amplifying the pump radiation at wavelength λ_2 such that pump radiation at wavelength λ_2 receives gain from the pump radiation at wavelength λ_1 , wherein the pump radiation at λ_1 and the pump radiation at λ_2 are non-information-bearing optical signals and wherein $\lambda_1 < \lambda_2$.

In accordance with the invention there is provided a multi-wavelength pump source for optical fibre amplification comprising:

- 10 a high power light source for providing a first non-information-bearing signal having a predetermined wavelength λ_1 ;
- a plurality of other light sources for providing a plurality of other non-information-bearing signals having wavelengths $\lambda_2, \lambda_3, \dots \lambda_p$, each of the plurality of other non-information-bearing signals having lower power and a longer wavelength than the first non-information-
- 15 bearing signal; and
- a section of optical waveguide for propagating the first non-information-bearing signal and the plurality of other non-information-bearing signals therethrough such that each of the plurality of other non-information-bearing signals receives gain from the high power light source.

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Brief Description of the Drawings

Exemplary embodiments of the invention will now be described in conjunction with the drawings in which:

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FIG. 1 is a schematic diagram of an optical amplifier in accordance with the instant invention including a first fibre amplifier for pumping a second fibre amplifier, both amplifiers operating in a co-propagating configuration;

30 FIG. 2 is a schematic diagram of a prior art cascaded Raman amplifier;

FIG. 3 is a schematic diagram of the Raman amplifier depicted in Fig. 1 wherein the first fibre amplifier has a counter-propagating configuration;

FIG. 4 is a schematic diagram of the Raman amplifier depicted in Fig. 1 wherein the second fibre amplifier has a counter-propagation configuration and the first fibre amplifier has a co-propagating configuration; and

FIG. 5 is a schematic diagram of the Raman amplifier depicted in Fig. 1 wherein the first and second fibre amplifiers have a counter-propagating configuration.

Detailed Description

Referring to Fig. 1, there is shown an optical amplifying system in accordance with the instant invention. A first fibre Raman amplifier indicated generally at 10 is optically coupled to and receives pump light from the second fibre Raman amplifier indicated generally at 20. The second fibre Raman amplifier 20 receives pump light from a high power coherent light source 40 providing radiation of wavelength λ_1 for amplifying light injected from a plurality of other light sources 50, 60, 70, 80 providing radiation of wavelengths $\lambda_2, \lambda_3, \lambda_4, \dots, \lambda_p$. In general, λ_1 is significantly shorter than $\lambda_2, \lambda_3, \dots, \lambda_p$, and each of $\lambda_2, \lambda_3, \dots, \lambda_p$ are shorter in wavelength than the lowest wavelength of the optical signal 5 to be amplified in the first fibre Raman amplifier 10.

Preferably, the first fibre Raman amplifier 10 is a distributed Raman amplifier including a length of telecommunication grade transmission fibre, which is for example, 25 km long. In contrast, it is preferred that the second fibre Raman amplifier 20 is a discrete Raman amplifier including a spool of optical fibre, which is for example about 200 metres long. More specifically, it is preferred that the second Raman amplifier 20 is cascaded Raman amplifier similar to the prior art amplifier shown in Fig. 2.

Referring to Fig. 2, radiation to be amplified 21 is coupled into optical fibre 22. The radiation to be amplified 21 is an information-bearing telecommunications signal i.e., the radiation 21 is modulated. Pump radiation 23 from pump source 24 is also coupled into optical fibre 22.

Appropriately selected matched pairs of in-line refractive index gratings, e.g., 25a and 25b, 26a and 26b, and 27a and 27b, are disposed within the fibre 22. The centre wavelength for each of the grating pairs 25a and 25b, 26a and 26b, and 27a and 27b, is selected such that the pump radiation 23 is shifted to the desired wavelength i.e., it is cascaded through multiple Raman orders until it reaches the desired wavelength. For example, if the pump source 24 includes a CW Nd:YAG laser pumping at 1064 nm and the signal 21 is transmitted in the third telecommunications window (i.e., about 1310 nm), then the centre wavelengths of the cavities are selected to be 1117 nm, 1175 nm and 1240 nm, respectively, and the pump energy is cascaded through four orders of Stokes shift, namely: 1117 nm, 1175 nm, 1240 nm, and 1310 nm. Once the pump radiation is within the desired range, the radiation to be amplified 21 is amplified by stimulated emission.

Although it is preferred that the second Raman amplifier 20 be similar to the cascaded Raman amplifier shown in Fig. 2, it is unique in that the pump source 40 pumps a plurality of other 'pump' sources 50, 60, 70, 80 (i.e., the plurality of other pump sources get gain from the high power pump source 40). More specifically, both the pump source 40 and the plurality of other 'pump' sources provide non-information-bearing signals.

Alternatively, the second fibre Raman amplifier 20 is a discrete Raman amplifier including a spool of optical fibre and an appropriately selected micro-optic wavelength division multiplexer (WDM).

Preferably, the high power coherent light source 40 is a single mode laser, such as a cladding pumped Yb or Nd fibre laser, which advantageously has variable power capabilities. The plurality of other light sources 50, 60, 70, 80 are preferably single wavelength lasers such as single frequency distributed feedback (DFB) laser diodes. Alternatively, the plurality of other light sources 50, 60, 70, 80 are Fabry Perot (FP), distributed Bragg reflector (DBR), master oscillator-power amplifier (MOPA), or fibre Bragg grating Fabry Perot (FBG FP) lasers. A coupler 30, which is preferably a wavelength division multiplexer (WDM) is provided for injecting light from the plurality of other light sources 50, 60, 70, 80 into the second fibre Raman amplifier 20. A second coupler 15, which is preferably a WDM, is provided for coupling the

high power, multi-wavelength pump light into the first fibre amplifier. Other couplers are optionally provided as needed. For example, a separate coupler can be used to couple each of the pump wavelengths $\lambda_2, \lambda_3, \lambda_4 \dots \lambda_p$ into the first 10 or second 20, amplifiers. Alternatively, a circulator is provided for injecting light into the first and/or second amplifiers.

5

Notably, the cascaded fibre Raman amplifier 20 serves as a multi-wavelength, high power pump source for the distributed fibre Raman amplifier 10, in accordance with the instant invention.

Advantageously, the amplifying system disclosed herein includes adjusting means for adjusting at least one of a gain, a power, and/or a gain shape. In particular, the adjusting means includes the use of multiple selected wavelengths, a controllable power level of each of the multiple wavelength sources 50, 60, 70, and 80 and/or a controllable power level of the high power source 40.

15 In operation, the high power light source 40 pumps light of wavelength λ_1 into a section of optical fibre of the cascaded Raman amplifier 20. Light corresponding to wavelength λ_1 is cascaded through a plurality of Raman orders, as discussed above, via stimulated Raman scattering until the high power pump light has a wavelength close to, but shorter than $\lambda_2, \lambda_3, \lambda_4$, and/or λ_p . Simultaneously, the single wavelength lasers providing radiation of wavelength $\lambda_2,$
 20 $\lambda_3, \lambda_4, \dots \lambda_p$ are multiplexed via WDM 30 and injected into the same section of optical fibre of the cascaded Raman amplifier 20. Since the "cascaded" pump light is shorter in wavelength but in the range of each of $\lambda_2, \lambda_3, \dots \lambda_p$, the energy provided by the high power light source 40 is largely converted to light having wavelengths $\lambda_2, \lambda_3, \dots \lambda_p$ via stimulated Raman scattering. As a result, a high power pump light having wavelengths $\lambda_2, \lambda_3, \lambda_4, \dots \lambda_p$ is provided. This multi-wavelength,
 25 high power pump light is coupled into the first fibre Raman amplifier 10 for amplifying a weakened information-bearing optical signal passing therethrough.

Advantageously, the instant invention realizes three advantages that have never been observed simultaneously in one Raman pump source: high power output, multiple wavelength output, and
 30 low noise operation.

High power output provides high gain. Since conversion efficiencies in the cascaded Raman amplifier disclosed herein are comparable to those in a cascaded Raman laser, the power of the single wavelength lasers are generally limited by the coupling of light from the high power coherent light source 40 to the second fibre Raman amplifier 20. Typically, the conversion efficiency for coupling light from a cladding pumped fibre laser to an optical fibre is >50% and for a cascaded Raman laser is ~ 50%.

Multiple wavelength output provides controllable gain shape. In the instant invention, the second fibre amplifier 20 transfers pump energy from the high power, coherent light source 40 to light from the single wavelength lasers, thus providing amplification in the spectral range of the single wavelength lasers. Multiple wavelength output can also increase bandwidth. Typically, the gain shape is controlled by controlling the input power of the single wavelength lasers 50, 60, 70 and 80. For example, the input power could be lower for longer wavelengths and higher for shorter wavelengths. Alternatively, each laser diode is switched between on and off states according to the desired gain profile.

Low noise pump operation allows for an increase in distance between optical amplifiers, and also allows lower signal powers to be used. The multi-wavelength source of the instant invention exhibits a relatively high signal-to-noise ratio, primarily due to the flexibility in choosing stable components. For example, single frequency DFBs that may be used as the single frequency lasers show exceptional stability and low noise since there is only one longitudinal mode lasing e.g., the noise from the interaction between pump and signal radiation is minimized.

Furthermore, low noise pump operation makes the instant invention compatible with co-propagating and/or counter-propagating configurations. This is in contrast to prior art Raman amplifiers, which have traditionally been restricted to a counter-propagating configuration to reduce noise (e.g., U.S. Pat. Nos. 5,673,280 and 5,623,508 incorporated herein by reference). In fact, each fibre Raman amplifier 10, 20 is capable of operating in either a co-propagating or counter-propagating pumping configuration, as illustrated in Figs. 3-5. In particular, Fig. 3 is a schematic diagram wherein the first fibre amplifier has a counter-propagating configuration; Fig. 4 is a schematic diagram wherein the second fibre amplifier has a counter-propagation

configuration and the first fibre amplifier has a co-propagating configuration; and Fig. 5 is a schematic diagram wherein the first and second fibre amplifiers have a counter-propagating configuration. In these figures like reference numerals illustrate like components. Notably, there is some degree of flexibility and/or variability in the coupling schemes.

5

Increased flexibility and certain cost advantages are realized in the availability in choice of the single high power coherent pump source 40. In fact, since the instant invention exploits cascaded Raman amplification, any of a multitude of predetermined wavelengths are suitable.

- 10 Of course, numerous other embodiments may be envisaged, without departing from the spirit and scope of the invention.

Claims

What is claimed is:

- 5 1. An optical amplifying system comprising:
a first Raman amplifier for amplifying an information-bearing optical signal; and
a second Raman amplifier optically coupled to the first Raman amplifier for amplifying a
non-information-bearing optical signal for pumping the first Raman amplifier.
- 10 2. An optical amplifying system as defined in claim 1, comprising a first coupler for introducing
the amplified non-information-bearing optical signal into the first Raman amplifier.
3. An optical amplifying system as defined in claim 2, comprising a second coupler for
introducing a high power optical signal having wavelength λ_1 and a lower power optical signal
15 having wavelength λ_2 into the second Raman amplifier, the high power optical signal λ_1
cascading through multiple Raman orders until it is within a suitable range from λ_2 such that λ_2
is selectively amplified to produce the amplified non-information-bearing optical signal.
4. An optical amplifying system as defined in claim 3, wherein λ_1 is from a cladding pumped
20 laser and λ_2 is selected from one of a DFB, DBR, MOPA, FP and FBG FP laser.
5. An optical amplifying system as defined in claim 4, wherein at least one of the first and
second couplers is a WDM.
- 25 6. An optical amplifying system as defined in claim 4, wherein at least one of the first and
second couplers is a circulator.
7. An optical amplifying system as defined in claim 4, wherein each of the first and second
Raman amplifiers is adapted to be pumped in one of a counter-propagating and a co-propagating
30 direction.

8. An optical amplifying system as defined in claim 7, wherein the second coupler is for further introducing a plurality of other lower power optical signals $\lambda_3, \lambda_4 \dots \lambda_p$ into the second Raman amplifier, the high power optical signal λ_1 cascading through multiple Raman orders until it is within a suitable range from $\lambda_3, \lambda_4 \dots \lambda_p$ such that $\lambda_3, \lambda_4 \dots \lambda_p$ are selectively amplified to produce
5 an amplified multi-wavelength non-information-bearing optical signal for pumping the first Raman amplifier.

9. An optical amplifying system as defined in claim 8, comprising adjusting means for adjusting at least one of a gain, a power, and a gain shape.

10. A pump source for optical fibre amplification comprising:

a first pump source for providing pump radiation at a first wavelength λ_1 ,

a second pump source for providing pump radiation at a second wavelength λ_2 ; and

a cascaded Raman amplifier optically coupled to the first and second pump sources for

15 allowing the pump radiation at wavelength λ_1 to be shifted to about wavelength λ_2 via stimulated Raman scattering and for amplifying the pump radiation at wavelength λ_2 such that pump radiation at wavelength λ_2 receives gain from the pump radiation at wavelength λ_1 , wherein the pump radiation at λ_1 and the pump radiation at λ_2 are non-information-bearing optical signals and wherein $\lambda_1 < \lambda_2$.

20 11. A pump source as defined in claim 10, wherein the first pump source is a cladding pumped fibre laser.

25 12. A pump source as defined in claim 11, wherein the second pump source is a single frequency distributed feedback laser.

13. A pump source as defined in claim 11, wherein the second pump source is selected from one of a DFB, DBR, MOPA, FP and FBG FP laser.

14. A pump source as defined in claim 12, comprising a WDM for coupling the first and second pump sources to the cascaded Raman amplifier.

15. A pump source as defined in claim 12, wherein the first and second pump sources are
5 arranged in a counter-propagating configuration.

16. A pump source as defined in claim 12, wherein the first and second pump sources are arranged in a co-propagating configuration.

10 17. A multi-wavelength pump source for optical fibre amplification comprising:
a high power light source for providing a first non-information-bearing signal having a predetermined wavelength λ_1 ;
a plurality of other light sources for providing a plurality of other non-information-bearing signals having wavelengths $\lambda_2, \lambda_3, \dots \lambda_p$, each of the plurality of other non-information-
15 bearing signals having lower power and a longer wavelength than the first non-information-bearing signal; and
a section of optical waveguide for propagating the first non-information-bearing signal and the plurality of other non-information-bearing signals therethrough such that each of the plurality of other non-information-bearing signals receives gain from the high power light
20 source.

18. A multi-wavelength pump source for optical fibre amplification as defined in claim 17, wherein the section of optical waveguide comprises a plurality of spaced apart reflectors for cascading the high power source λ_1 through a plurality of Raman orders until it is within range of
25 at least one of the plurality of other non-information-bearing signals having wavelengths $\lambda_2, \lambda_3, \dots \lambda_p$.

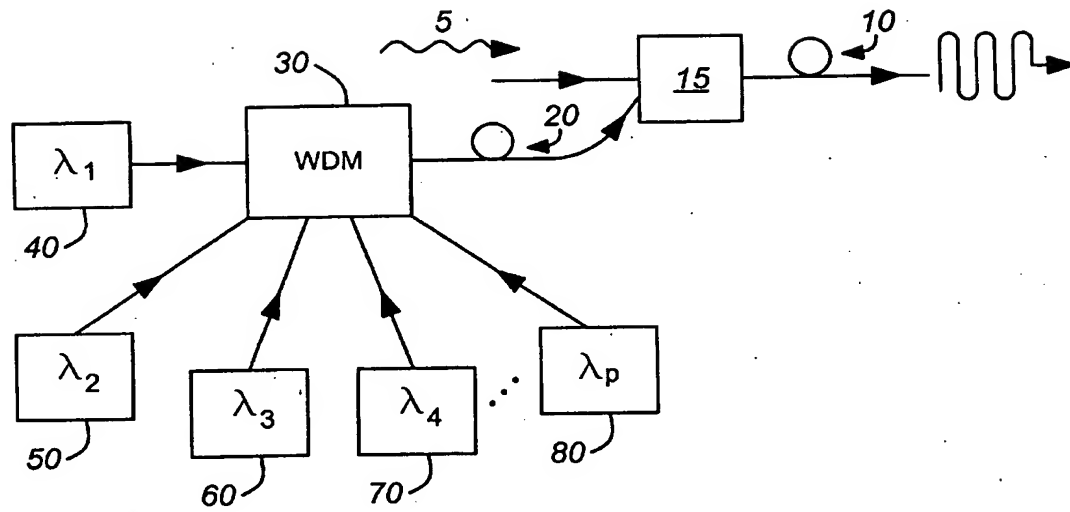
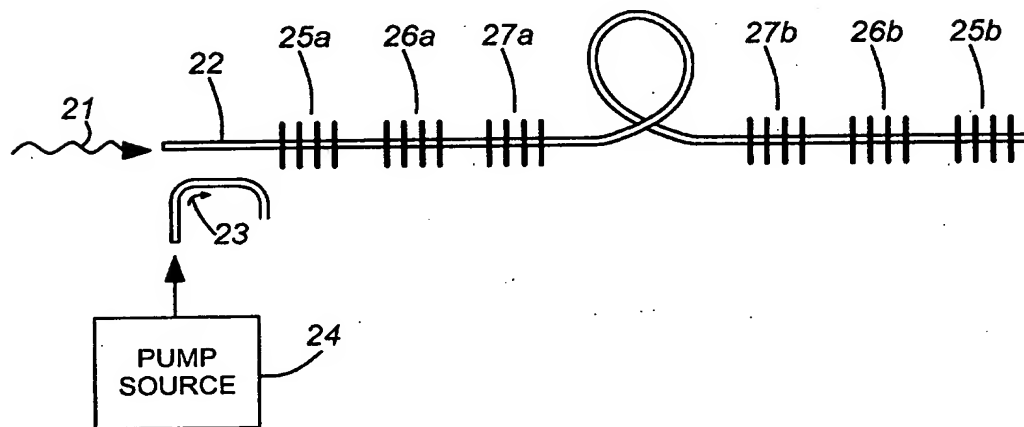
19. A multi-wavelength pump source for optical fibre amplification as defined in claim 17, wherein the section of optical waveguide includes a micro-optic WDM for cascading the high
30 power source λ_1 through a plurality of Raman orders until it is within range of at least one of the plurality of other non-information-bearing signals having wavelengths $\lambda_2, \lambda_3, \dots \lambda_p$.

20. A multi-wavelength pump source for optical fibre amplification as defined in claim 18, comprising a WDM for coupling the plurality of other non-information-bearing signals having wavelengths $\lambda_2, \lambda_3, \dots \lambda_p$ into said section of optical waveguide.

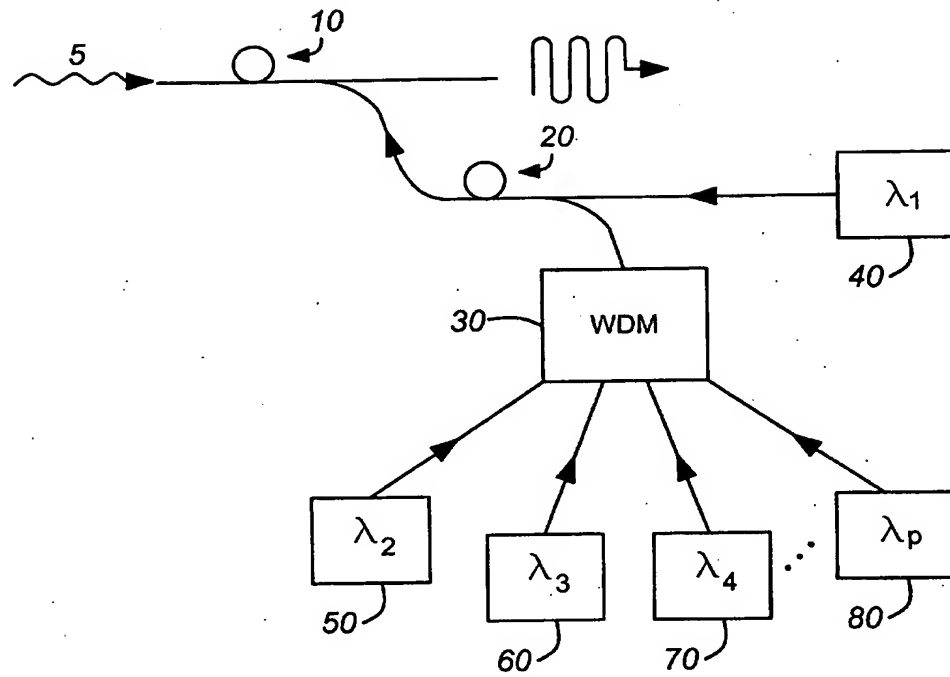
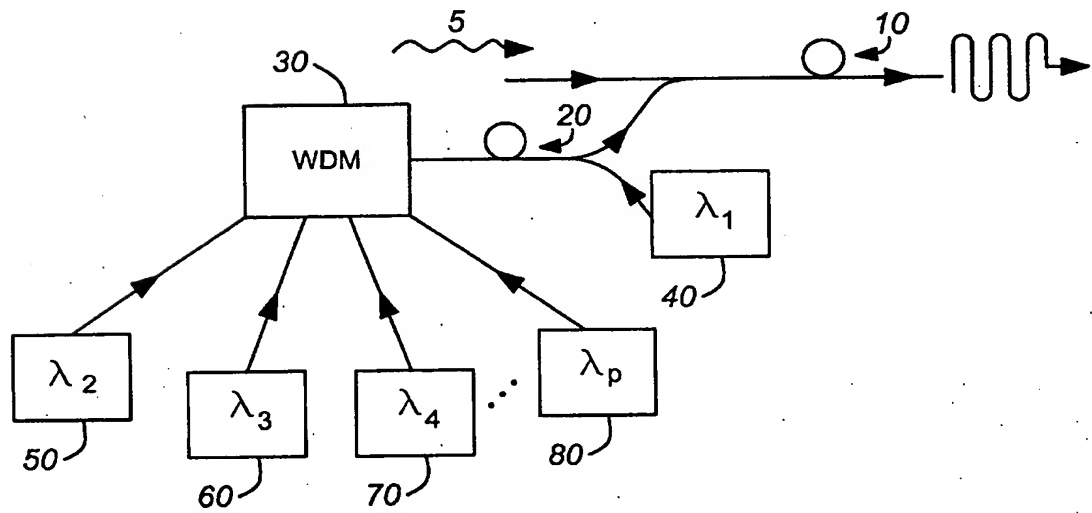
5 21. A multi-wavelength pump source for optical fibre amplification as defined in claim 20, wherein the high power light source λ_1 is a cladding pumped fibre laser.

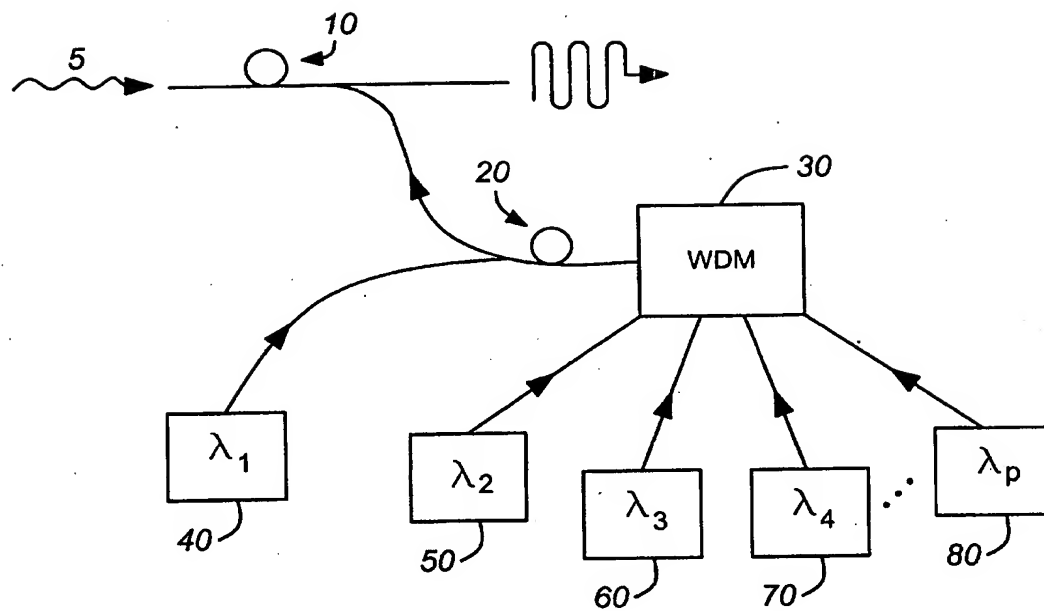
22. A multi-wavelength pump source for optical fibre amplification as defined in claim 21, wherein the plurality of other light sources $\lambda_2, \lambda_3, \dots \lambda_p$ are single frequency distributed feedback
10 laser diodes.

23. A multi-wavelength pump source for optical fibre amplification as defined in claim 22, wherein an input power for each of the distributed feedback laser diodes is adjustable for
15 controlling the gain profile.

**FIG. 1**

PRIOR ART
FIG. 2

**FIG. 3****FIG. 4**

**FIG. 5**